TITLE OF THE INVENTION

Magnetic Resonance Imaging Apparatus

FIELD OF THE INVENTION

The present invention relates to a magnetic resonance imaging apparatus (hereinafter will be called as MRI apparatus) which makes use of nuclear magnetic resonance phenomenon and permits to obtain a tomographic image of any desired positions of a subject and in particular, relates to a technology for preventing an image quality deterioration such as image distortion, signal intensity reduction and ghosting which is caused by a gradient magnetic field waveform distortion due to eddy current induced by an application of gradient magnetic field.

BACKGROUND ART

An MRI apparatus causes atomic nuclear (usually proton) existing in any desired regions of a subject nuclear magnetic resonance phenomenon through application of high frequency magnetic field on to the subject placed in homogeneous static magnetic field and obtains a tomographic image of the region from nuclear magnetic resonance signals (echo signals) induced thereby. In this instance, in order to select a specific region, a gradient magnetic field is applied together with the high frequency magnetic field and further, in order to provide correct positional information for the echo signals measured, it is necessary to correctly

control the application time and intensity of the gradient magnetic field.

However, actually due to the gradient magnetic field application, currents with damping property are induced in a variety of structural bodies around gradient magnetic coils. Such current induced with damping property is called as eddy current, which shows a different time constant component depending on types of magnets used for static magnetic field generation. For example, a time constant of a permanent magnet type apparatus is about 1 sec. and a time constant of a superconductive magnet type apparatus reaches up to about 2 sec. These eddy currents generate magnetic field varying spatially and temporally and cause to deviate the gradient magnetic field sensed by nuclear spins in the subject from an ideal condition. Thereby, reduction of image quality such as image distortion, signal intensity reduction and ghosting is induced.

In order to prevent such image quality reduction due to eddy currents, a method has been developed, in which the spatially and temporally varying magnetic field is measured and the magnetic field variation is compensated. For example, JP-A-10-272120 discloses a technology in which a phantom is disposed in a static magnetic field space, after applying a test gradient magnetic field a high frequency pulse is applied, NMR signals caused thereby are measured, magnetic field

variation due to eddy currents caused by the application of the test gradient field is measured along with discrete time lapse, compensation currents for compensating the magnetic field variation are respectively determined and an influence affected to the magnetic field by the gradient field applied at the time when taking an image of a subject is avoided.

In the above method, after applying the test gradient magnetic field, nuclear spins in the phantom are excited by high frequency (RF) pulses and phase encoded free induction decay signals (FID signals) are sampled in a predetermined period. The measurement of the FID signals is repeated by varying the phase encode amount and a set of data of two dimensions or three dimensions is obtained. The FID signals contain, other than the eddy currents induced by the test gradient magnetic field, influences of inhomogeneity of the static magnetic field and eddy current due to the phase encoding gradient magnetic field. Thus, by changing the polarity of the test gradient magnetic field, a similar measurement is performed to obtain another set of data, through taking difference of the two sets of data obtained in the two measurements, the influences of inhomogeneity of the static magnetic field and eddy current due to the phase encoding gradient magnetic field are avoided. Thus, a phase difference image, which only contains the influence of eddy currents induced

by the test gradient magnetic field, is obtained. Based on the phase difference image, magnitudes of the eddy currents are resolved spatially and temporally and their time constants are calculated and compensation currents to be flown in the gradient magnetic field coils and shim coils are calculated.

As has been explained above, in the conventional method, the following operation is repeated, in that after applying the test gradient magnetic field, the RF pulses of non-selectivity are applied, the phase encoding is performed in three axial directions, the FID signals are sampled along time lapse and four dimensional data containing time axis are obtained.

However, since the FID signals measured with the conventional art decay according to lapse of time, a level of NMR signals for measuring an eddy current having a long time constant reduces according to time, namely, since S/N reduces according to lapse of time, it is afraid that the measurement accuracy of eddy currents having a long time constant will be reduced.

Further, the eddy currents induced by the application of the gradient magnetic field are caused when the gradient magnetic field rises and falls and differences in the induced currents at the time when rising and falling of the gradient magnetic field application is sometimes caused due to such as vibration of structural bodies of magnet disposed around the

gradient magnetic field coils. However, the measurement object in the above conventional art is limited only to the eddy current components induced at the time when the gradient magnetic field falls, and the conventional

5 art does not disclose to measure the influence to the magnetic field due to the eddy current component induced when the gradient magnetic field rises and to compensate the same.

An object of the present invention is to provide

10 an MRI apparatus which measures the eddy current components having a long time constant induced when the gradient magnetic field rises and /or falls and permits to compensate with a high accuracy the influence to the magnetic field caused thereby.

15 SUMMARY OF THE INVENTION

In the present invention which achieves the above object, a phantom is disposed in static magnetic field, gradient magnetic field having a predetermined intensity is applied in a predetermined gradient

20 magnetic field application axis direction for a longer time than a time constant of an eddy current to be compensated, a pulse sequence is started which measures a spatial distribution of magnetic field in response to ON and/or OFF of the applied gradient magnetic field

25 as well as the pulse sequence is repeated in a plurality of times with repetition time TR while changing phase encoding amount, a variation state of the magnetic field

caused by the induced eddy current is measured from an image, a current value to be flown in to a magnetic field variation compensation coil is determined from the measured value for successively compensating variation state of the magnetic field and the determined current value for compensating the magnetic field variation is supplied to the magnetic field variation compensation coil when a pulse sequence for actually taking an image of a subject is performed.

Further, the gradient magnetic field applied for a longer time than the time constant of the concerned eddy current can be applied either in a form of actual value or in a form of effective value.

Still further, the spatial distribution of the magnetic field due to the eddy current caused by ON and/or OFF of the gradient magnetic field is measured in a plurality of times in an equal time interval along with lapse of time.

In a further preferred embodiment, for the measurement of spatial distribution variation of the magnetic field due to the eddy current caused when the gradient magnetic field is turned ON, through performing a pulse sequence for measuring echo signals containing application of a test gradient magnetic field in a plurality of times (n) with repetition time TR, an application of a gradient magnetic field having a longer time than the time constant of an eddy current

to be compensated is substantially realized as well as the pulse sequence is performed repeatedly to obtain an MR image, a spatial distribution of the magnetic field due to the eddy current is measured from the obtained MR image, and then, a current value to be flown in to the magnetic field variation compensation coil for compensating the magnetic field spatial distribution is determined.

Further, for the measurement of spatial distribution variation of the magnetic field due to the eddy current caused when the gradient magnetic field is turned OFF, prior to the measurement of the magnetic field variation due to the eddy current, the pulse sequence for magnetic field measurement containing the magnetic field variation due to the eddy current caused when the gradient magnetic field is turned ON is performed while modifying the same so as not to measure the echo signals, following this pulse sequence a pulse sequence for measuring echo signals is repeatedly performed with the repetition time TR to obtain an MR image, a variation state of the magnetic field due to the eddy current is measured from the obtained MR image, and then, a current value to be flown in to the magnetic field variation compensation coil for compensating the magnetic field spatial distribution is determined.

Further, according to the present invention, a compensation of both influences when the gradient

magnetic field is turned ON/OFF can be realized by performing in combination the measurement sequences when the gradient magnetic field is turned ON and OFF.

BRIEF DESCRIPTION OF THE DRAWINGS

5   Fig.1 is a diagram showing an outline of an MRI apparatus to which the present invention is applied;

Fig. 2 is a flowchart showing an example of sequences for measuring eddy currents and for compensating magnetic field variation based on the

10   measurement in the MRI apparatus according to the present invention;

Fig. 3 is a diagram showing an example of calibration pulse sequences provided in the MRI apparatus according to the present invention;

15   Fig. 4 is a diagram showing another example of calibration pulse sequences provided in the MRI apparatus according to the present invention; and

Fig. 5 is a diagram showing a still another example of calibration pulse sequences provided in the MRI

20   apparatus according to the present invention.

BEST MODE EMBODIMENTS FOR CARRYING OUT THE INVENTION

Embodiments of the present invention will be explained herein below.

25   Fig.1 is a block diagram showing an entire outline of an MRI apparatus to which the present invention is applied. The MRI apparatus comprises, as its primary

constituents, a static magnetic field generating magnetic circuit 1 for generating homogeneous static magnetic field in a space where a subject 9 is placed, a gradient magnetic field generating system 2 for

5 providing magnetic field gradient to the static magnetic field, a signal transmission system 3 for generating high frequency (RF) magnetic field which causes nuclear magnetic resonance phenomenon in atomic nuclei (usually proton) of atoms constituting tissue

10 of the subject 9, a signal receiving system 4 for receiving echo signals generated from the tissue of the subject 9 through the nuclear magnetic resonance phenomenon, a signal processing system 5 which processes the echo signals received by the signal

15 receiving system 4 and reconstructs an image representing such as spatial density and spectrum of atomic nuclei in the tissue and a central processing unit (CPU) 7 which performs a variety of operations in the signal processing system 5 and of controls for the

20 entire apparatus.

The static magnetic field generating magnetic circuit 1 is constituted by either a permanent magnet, a normal conductivity type magnet or a superconductivity type magnet, and generates a

25 homogeneous static magnetic field around the subject 9 in its body axis direction or in the direction perpendicular to the body axis. The gradient magnetic

field generating system 2 is constituted by gradient
magnetic field coils being wound so as to generate
gradient magnetic fields in three axial directions of
x, y and z and gradient magnetic field power sources

5 11 which drive respective gradient magnetic field coils
and through driving the gradient magnetic field power
sources for the respective coils according to the
command from a sequencer 6 which will be explained later,
gradient magnetic fields Gx, Gy and Gz in three axial

10 directions of x, y and z are applied to the subject 9.
According to application manners of the gradient
magnetic fields, an image taking object region (slice,
slab) of the subject 9 can be set as well as positional
information such as phase encoding and frequency

15 encoding can be provided for the echo signals.

Further, although not illustrated, in the static
magnetic field generating magnetic circuit 1 and the
gradient magnetic field generating system 2, shim coils
(such as x-y coils and z^2 coils) are disposed for

20 compensating variation in magnetic field induced by
such as inhomogeneity of static magnetic field and eddy
currents due to the gradient magnetic field. Further
the gradient magnetic field coils 10 function as shim
coils for correcting first orders thereof.

25 The signal transmission system 3 is for
irradiating a high frequency magnetic field (RF pulses)
for causing nuclear magnetic resonance phenomenon in

atomic nuclei of atoms constituting the living body tissue of the subject 9 by means of the high frequency pulses sent out from the sequencer 6 and is constituted by a high frequency oscillator 12, a modulator 13, a

5   high frequency amplifier 14 and a high frequency coil 15 at the signal transmission side. In the signal transmission system 3, the high frequency pulses output from the high frequency oscillator 12 are amplitude modulated by the modulator 13, after amplifying the

10 amplitude modulated high frequency pulses by the high frequency amplifier 14, the same are supplied to the high frequency transmitting coil 15, thereby, high frequency magnetic field (RF electro magnetic pulses) are irradiated to the subject 9.

15   The signal receiving system 4 is for detecting echo signals (NMR signals) sent out from the subject 9 through nuclear magnetic resonance phenomenon and is constituted by a high frequency receiving coil 16 at the signal receiving side, an amplifier 17, an

20 orthogonal phase detector 18 and an A/D converter 19. In the signal receiving system, echo signals detected by the high frequency receiving coil 16 are input via the amplifier 17 and the orthogonal phase detector 18 in to the A/D converter 19 to convert the same in to

25 digital signals and are sent to the signal processing system 5 as collected data in two series.

    The signal processing system 5 is constituted by

a CPU 7, a ROM 20, a RAM 21, a recording device such as an optical disk 22 and a magnetic disk 24 and a display such 23 as a CRT, and the CPU 7 performs such as Fourier transformation, correction coefficient calculation

5   and image reconstruction processing and displays the obtained image on the display 23. The ROM 20 stores such as programs for performing image analysis processing and measurement and parameters used when executing the programs. The RAM 21 stores temporarily such as

10   measurement parameters obtained during preliminary measurement, echo signals obtained by the signal receiving system 4 and images used for setting a region of interest as well as stores such as parameters for setting the region of interest. The optical disk 22 and

15   the magnetic disk 24 work as a data storage portion for storing images reconstructed at the CPU 7. An operating portion 8 is for an operator inputting such as selection commands and parameters of a pulse sequence for image taking as well as for inputting control information of

20   the processing performed in the signal processing system 5 and is constituted by such as a truck ball or a mouse 25 and a keyboard 26.

Other than the above operations, the CPU 7 sends via the sequencer 6 a variety of commands necessary for

25   data collection for a tomographic image of the subject 9 to the gradient magnetic field generating system 2, the signal transmission system 3 and the signal

receiving system 4. The sequencer 6 controls the gradient magnetic field generating system 2, the signal transmission system 3 and the signal receiving system 4 according to a pulse sequence which is a time chart

5   for a predetermined control determined by the concerned image taking method and controls data collection necessary for image reconstruction.

The pulse sequence of the MRI apparatus according to the present invention includes, other than a usual

10   image taking pulse sequence, a calibration pulse sequence for measuring eddy currents induced by gradient magnetic field which is performed, for example, at the time of installation of the MRI apparatus, at the time of reconstruction and at the time of parts

15   exchange and these pulse sequences are installed in the ROM 20 as programs.

Now, measurement of the eddy currents performed by the MRI apparatus with such constitutions and compensation method of the magnetic field variation

20   based on the measurement will be explained. Fig.2 is a flowchart showing a sequence of the eddy current measurement and the compensation of the magnetic field variation based on the measurement, and Fig.3 is a diagram showing an example of calibration pulse

25   sequences for measuring temporal and spatial magnetic field variation induced by the eddy currents. The illustrated calibration pulse sequence shows one

suitable for measuring eddy currents induced when the gradient magnetic field falls, and for measuring eddy currents induced when the gradient magnetic field rises, a modified pulse sequence thereof can be used. The

5   manner of the modification will be explained later.

At first, by executing the calibration pulse sequence, the eddy current measurement is performed (steps 201~207). The measurement is performed after arranging a usual phantom at the center of the static

10   magnetic field. As the phantom, a spherical one is preferable for minimizing influence of magnetic susceptibility.

As shown in Fig.3, the calibration pulse sequence is based on a short TR pulse sequence according to a

15   gradient echo method and is constituted by a unit in which a test gradient magnetic field is applied (herein after called as group 1) and another unit in which no test gradient magnetic field is applied (herein after called as group 2).

20   At first, the measurement of eddy current induced when the gradient magnetic field falls will be explained. In this instant, the unit of group 1 exists for applying the test gradient magnetic field. The test gradient magnetic field is required to be applied with a

25   predetermined intensity in a predetermined axial direction, in the most simple manner, the test gradient magnetic field is required to be applied at least once

prior to the group 2, moreover, the test gradient magnetic field is required to be applied so that the gradient magnetic field falls after the eddy currents induced when the gradient magnetic field rises have

5   disappeared. For this purpose, as the gradient magnetic field indicated by Geff in Fig.3, if the time constant of an eddy current of the measurement object is, for example, 2 sec., it is required to apply a gradient magnetic field for an interval more than 2 sec. However,

10   in order that a gradient magnetic field is generated for a long time such as 2 sec., since a large current has to be flown for a long time in the gradient magnetic field coils, it is afraid that adverse influences thereby, for example, such as the heat generated in the

15   gradient magnetic field coils and deformation and disconnection of the gradient magnetic field coils by the heat are caused.

Therefore, in the present embodiment, the test gradient magnetic field is divided in a pulse shape and

20   is applied in a divided manner in a plurality of times so that an effective gradient magnetic field Geff is applied in a temporally continued manner. Thereby, the turning OFF of the gradient magnetic field can be realized after the eddy current induced when the

25   gradient magnetic field rises has disappeared, accordingly, it is designed that only the eddy current induced when the gradient magnetic field falls can be

measured in the group 2. Herein below, under the precondition of the above explanation, the sequence will be explained in more detail.

In the group 1 unit of the pulse sequence, by making use of an RF excitation pulse 101 and a slice selection gradient magnetic field 102 any desired cross section of a phantom is excited, after encoding in phase direction the excited nuclear spins through application of a phase encode gradient magnetic field 103, and after causing to generate an echo signal 106 through application of a read out direction gradient magnetic field 104 (however, the echo signal is not sampled), a test gradient magnetic field 1051 having a predetermined intensity and a predetermined application time is applied. The same sequence is repeated with a repetition time TR (for example, TR=10 msec.) in a plurality of times (n times, for example, n=300), and through the repetition of the sequence, the test gradient magnetic fields from 1052 (not illustrated) to 105n are applied. Accordingly, time for executing the group 1 once is required for 3 sec. During this repetition, the phase encode gradient magnetic field 105 is kept at a same application amount. When assuming the intensity and the application time of the test gradient magnetic field 105 as Gtest and tG, the gradient magnetic field which the nuclear spins felt by the test gradient magnetic fields 105 repeatedly

applied in group 1 is substantially equivalent as those when the gradient magnetic field having effective magnetic field intensity of $Geff=Gtest \times tG/TR$ is continuously applied for time $TR \times n$ times. When assuming that the repetition time TR is 10 msec. and n is 300, since it is assumed that the effective gradient magnetic field Geff is continuously applied for an interval of about 3 sec., it is considered that the eddy current having time constant of 2 sec. which is induced when the effective gradient magnetic field Geff rises has disappeared at the time when the effective gradient magnetic field Geff falls. Further, the eddy currents due to the application of the test gradient magnetic fields 105, in that due to Geff are induced at the time when rising of Geff application and falling thereof, and damp as shown in Fig.3.

In the group 1, since the gradient echo sequence including the slice selective RF excitation is repeatedly performed 300 times exceeding 100 times with the short repetition time of 10 msec., the nuclear spins in the region repeatedly subjected to the selective excitation within the phantom are placed in a steady state free precession (SSFP) state and an advantage is achieved that the echo signals measured in group 2 escape from an unstable vibrating state and are stabilized.

After completing execution of the pulse sequence

groups in the group 1, the pulse sequence groups in the group 2 are executed. In the group 2, like the group 1, after applying an RF excitation pulse 101, a slice selection gradient magnetic field 102 and phase encode

5   gradient magnetic field 103 to the same cross section of the phantom in the same manner as performed in the group 1, an echo signal 106 is caused to generate through application of a read out direction gradient magnetic field and the echo signal 106 is measured in a sampling

10 period 107. Following the TR' (1), thereafter, without applying the test gradient magnetic field like the TR' (1), the same pulse sequence is repeated with repetition time TR' (=TR) in a plurality of times (n times, for example, 300 times). The application amount of the phase

15 encode gradient magnetic field 103 used in the pulse sequence in the respective units in the group 2 is the same as that in the group 1. Since the signals measured in every repetition time TR' in the group 2 are the echo signals having the same level, and no level variation

20 according to lapse of time is caused different from when the FID signals in the above referred to conventional art are sampled in every time point ti. Accordingly, S/N is kept constant and an eddy current having a long time constant can be measured with a high accuracy.

25   By making the calibration sequence consisting of the groups 1 and 2 as a unit, and repeating the unit m times (m is, for example, 64) while changing the phase

encode amount every time, finally, three dimensional data set S (kx,ky,ti)containing time as variable is obtained (step 201). Wherein, kx and ky represent spatial frequency and ti represents a discrete time point (I=1,2,3,···n), when the echo signals obtained every TR' in group 2 are orderly arranged. Namely, the data set is what is resolved with regard to time of the spatial magnetic field variation in the measurement time (time for executing the group 2, TR' x n), and through setting the repetition times n and the repetition time TR', the measurement time of the magnetic field variation and time resolution can be set as desired.

Thus measured data set of magnetic field variation contains the magnetic field variation due to the eddy current induced when the test gradient magnetic field applied in group 1 falls as well as contains an influence of inhomogeneous static magnetic field and influences of eddy currents due to the gradient magnetic fields 102, 103 and 104 applied for imaging.

Therefore, by changing the test gradient magnetic field 105 in to negative polarity as illustrated by dotted line in Fig.3, a series of calibration pulse sequence consisting of groups 1 and 2 is executed in the same manner as when the test gradient magnetic field 105 is positive polarity (step 202). Herein below, a calibration pulse sequence of which test gradient

magnetic field is positive is expressed as Scan(+) and a calibration pulse sequence of which test gradient magnetic field is negative is expressed as Scan(−). Subsequently, in order to take difference between data

5 set S+(kx,ky,ti) obtained in Scan(+) and data set S−(kx,ky,ti) obtained in Scan(−), at first, these data sets are subjected to 2D Fourier transformation for every time point ti and time resolved 2D complex image data I+(x,y,ti) and I−(x,y,ti) are obtained (steps 203

10 and 204). From arctangent of the ratio between the real part and the imaginary part of these complex image data, phase image data ϕ+(x,y,ti) and ϕ−(x,y,ti) for every time point are obtained (steps 205 and 206). Thereafter, by taking difference thereof, data set ϕ(x,y,ti)(=[ϕ

15 +(x,y,ti)− ϕ −(x,y,ti)]/2) is obtained in which the influence of inhomogeneous static magnetic field and influences of eddy currents due to the gradient magnetic fields applied for imaging are removed (step 207). ϕ (x,y,ti) represents a phase variation amount during TE

20 (echo time) at position (x,y) and time point ti caused by magnetic field variation B(x,y,ti) due to the eddy current induced when the test gradient magnetic field falls. B(x,y,ti) is given as B(x,y,ti)=ϕ(x,y,ti)/γ TE. Further, γ is the gyromagnetic ratio. Thereby,

25 spatial (2D) magnetic field variation due to the eddy current induced by the test gradient magnetic field applied in group 1 is measured with time resolution of

TR. Subsequently, by making use of the phase difference image which is the present measurement result, compensation currents to be supplied for the gradient magnetic field coils and the shim coils are calculated

5 (step 208~210). Then, the compensation currents determined at step 210 are caused to flow in the gradient magnetic field coils and the shim coils when performing an actual image measurement for a subject (step 211). The currents to be flown in the gradient magnetic field

10 coils or the shim coils are determined according to a ratio between the test gradient magnetic field and the gradient magnetic field at the time of the image measurement or a ratio between currents to be flown in to the gradient magnetic field coils for applying these

15 gradient magnetic fields.

As the method of determining the compensation currents from the magnetic field variation for generating magnetic field for compensating the magnetic field variation, either any conventional methods or the

20 simplified method as shown in Fig.2 can be used. As one of the conventional methods, a common method, which is also disclosed in the above referred to JP-A-10-272120, will be explained briefly. At first, magnetic field Bt(x,y) induced by an eddy current at a predetermined

25 time point ti is expressed as a sum of spherical harmonics as shown in the following formula;

$$Bti(x, y) = \zeta_{00,ti} + \zeta_{11,ti}\, x + \zeta_{12,ti}\, y + \zeta_{21,ti}(x^2 - y^2) + \zeta_{22,ti}xy + \cdots \qquad \cdots (1)$$

By performing development of these spherical harmonics at respective time points, a set of coefficients ζ of the spherical harmonics which depend on time are obtained. It is known that the respective coefficients ζ are related to the magnitudes of the eddy currents resolved with regard to space and the time constants thereof and from the relationship the compensation currents are determined. This method permits correction of high degrees of order and shows a high accuracy of correction, however, requires time for analysis and necessitates additional correction coils for the high degrees of order.

A simplified analysis method as shown in Fig.2 will be explained. As one of examples, an instance wherein the test gradient magnetic field 105 is applied for X axis will be explained. In the present method, among the eddy currents induced when the test gradient magnetic field 105 is applied for X axis, only first order gradient component g(ti) and polarization component B0(ti) are compensated.

For this reason, when presuming that the magnetic field variation B(x,ti) at position x and time ti is as B(x,ti)=g(ti) · x + B0(ti), from magnetic field variation B(x1,ti) and B(x2,ti) at any two points in the space of the static magnetic field, g(ti) and B0(ti) are calculated according to the following formulas (step 208);

$$g(ti) = [B(x1, ti) - B(x2, ti)]/(x1 - x2) \qquad \cdots (2a)$$

$$B0(ti) = [B(x1, ti) + B(x2, ti)]/2 - g(ti) \ (x1 + x2) \qquad \cdots (2b)$$

Herein, when two points satisfying x1=-x2 are selected, calculation of B0(ti) is further facilitated.

By making use of already known non-linear type fitting (for example, Levenberg-Marquardt method), thus calculated g(ti) and B0(ti) are resolved in to any number of time constants τ and amplitudes A and B for every time constant as in the following formulas, in which g0 and B0 are constants (step 209);

$$g(ti) = \Sigma \, Aj \cdot \exp(t/\tau j) + g0 \qquad \cdots (3a)$$

$$B0(ti) = \Sigma \, Bm \cdot \exp(t/\tau m) + B0 \qquad \cdots (3b)$$

The magnetic field variation due to the eddy currents is corrected by supplying compensation currents having the time constants and the amplitudes of opposite polarity to the gradient magnetic field coils or the shim coils for X axis direction (steps 210 and 211).

The present method is simple in comparison with the above referred to method using the development of spherical harmonics and moreover, the image quality deterioration due to the eddy current is sufficiently improved.

In the above explanation, although a method of compensating the eddy current caused by application of

gradient magnetic field in X axis by making use of X axis as the read out axis direction, since the gradient magnetic fields are applied in three axes of x, y and z for imaging of a subject, it is necessary to compensate

5   eddy currents induced by application of gradient magnetic fields in y axis and z axis. Such purpose can be realized by performing the measurement in the like manner while replacing the read out direction in Fig.3 separately to y axis and z axis.

10   In the above embodiment, a case where the magnetic field variation in 2D space due to eddy currents is compensated has been explained, the present invention is likely applicable the magnetic field variation in 3D space. Herein below, an embodiment for 3D case will

15   be explained. Fig.4 shows a calibration pulse sequence for the 3D case. In Fig.4, a relationship between the effective gradient magnetic field intensity Geff and the eddy current is the same as that in Fig.3, the illustration thereof is omitted.

20   Likely in the present embodiment, the calibration pulse sequence is constituted by a pulse sequence of group 1 in which a test gradient magnetic field 405 is applied and another pulse sequence of group 2 in which no test gradient magnetic field is applied but an echo

25   signal 406 is measured. However, the present embodiment uses a non-selective RF excitation pulse 401 as an RF excitation pulse and encode gradient magnetic fields

402 and 403 in two axial directions.

By performing respectively the pulse sequences of groups 1 and 2 with a same encode amount, echo signals (n pieces of signals) at respective time points ti are obtained. The pulse sequence is repeated while changing the phase encode amount for respective axes and finally, 4D data set S(kx,ky,kz,ti) including variable of time is obtained. Even in this instance, in order to remove the influences of eddy currents other than the eddy currents due to the test gradient magnetic fields, two measurements of Scan(+) and Scan(-) are performed while changing the polarity of the test gradient magnetic fields.

Data set S+(kx,ky,kz,ti) and S-(kx,ky,kz,ti) obtained by the two measurements are subjected to 3D Fourier transformation for every time point , 3D complex image data is obtained and further, phase image data $\phi+(x,y,z,ti)$ and $\phi-(x,y,z,ti)$ are obtained. From the difference of these phase image data phase difference image data is prepared and magnetic field B(x,y,z,ti) at any position (x,y,z) and time ti is calculated.

For thus calculated magnetic field B(x,y,z,ti), either the analysis making use of development of spherical harmonics or the simplified analysis as explained in connection with Fig.2 embodiment is applied and the magnetic field is resolved in to any desired number of time constant components and

amplitudes for every time constant component. By supplying compensation currents having the time constants and the amplitudes (magnitudes of the currents) to the concerned gradient magnetic field coils or the shim coils, the magnetic field variation due to the eddy currents is corrected.

Herein above, although the embodiments in which the influences due to eddy currents when the gradient magnetic field falls have been explained with reference to Figs.2~4, the MRI apparatus according to the present invention also can correct the influences due to the eddy currents induced when the gradient magnetic field rises. Herein below, such embodiment will be explained with reference to Fig.5.

Fig.5 is a diagram showing an example of calibration pulse sequence for measuring eddy currents induced when the gradient magnetic field rises. As illustrated in the drawing, the calibration pulse sequence is also constituted by a pulse sequence of group 1 and another pulse sequence of group 2, and like the calibration pulse sequence in Figs.3 and 4, the pulse sequences of the respective groups include an RF excitation pulse 501 and gradient magnetic fields 502~504 for image formation. However, according to the present embodiment, in the pulse sequence of group 1 the test gradient magnetic fields 505 (5051~505n) are applied as well as prior to the application echo signals

generated by an application of the read out gradient magnetic field 504 are sampled 507. In the pulse sequence of group 2, like the calibration pulse sequence in Fig.3, no test gradient magnetic field is applied and no echo signals are sampled. Namely, as explained in connection with Fig.3, the pulse sequence of group 2 is performed to place the nuclear spins in an SSFP state through repeating excitation with short TR and to stabilize the echo signals to be measured in group 1.

In this instance, the test gradient magnetic fields 5051~505n according to the pulse sequence of group 1 are equivalent to a continuous application of the gradient magnetic field having effective intensity Geff=Gtest X tG/TR for time TR x n times, and in the echo signals measured in the pulse sequence of group 1, a magnetic field variation due to the eddy currents induced when such test gradient magnetic fields 505 rise is contained.

In this instance, since the echo signals also contain the magnetic field variation other than the magnetic field variation due to the test gradient magnetic field (magnetic field variations due to inhomogeneous static magnetic field and gradient magnetic fields for image formation), in order to remove these variations the calibration pulse sequence is executed while changing the polarity of the test

gradient magnetic field and the difference of the data set obtained in the respective measurements is taken. In this instance, according to Fig.5 calibration pulse sequence, since time resolved data for every phase encode amount is obtained in the pulse sequence of group 1, the data is used as 3D data including variable of time to calculate the compensation currents later. A method of determining the amplitudes of the compensation currents and the time constants thereof from the phase difference data is exactly the same as the method as explained in connection with Fig.2 embodiment.

As has been explained above, according to the present calibration pulse sequence an eddy current induced at the time when the gradient magnetic field rises up can be properly corrected. Further, it will be easily understood that when measuring both eddy currents induced at the time when the test gradient magnetic field rises up and falls down, it will be sufficient if a calibration pulse sequence formed by combining the group 1 pulse sequence as shown in Fig.5 and the group 2 pulse sequence as shown in Fig.3 is performed.

Further, although the calibration pulse sequence as shown in Fig.5 shows a case wherein the phase encoding is performed for a single axis (a case of two dimension measurement), the present embodiment can also be

applied to the three dimension measurement as shown in Fig.4.

Since the principle of the present invention is to measure the echo signal containing the eddy current component during the calibration pulse sequence including the test gradient magnetic field application when measuring the eddy current induced at the time when the gradient magnetic field rises and, when measuring the eddy current induced at the time when the gradient magnetic field falls down, to measure the echo signal containing the eddy current component induced by the previous gradient magnetic field application during the calibration pulse sequence not including the test gradient magnetic field application after completing the calibration pulse sequence including the test gradient magnetic field application, the present invention can be realized by introducing a rest time in place of the group 2 pulse sequence group as shown in Fig.5 for measuring the eddy current induced at the time when the gradient magnetic field rises up and for measuring the eddy current induced at the time when the gradient magnetic field falls down by simply applying a test gradient magnetic field in place of the group 1 pulse sequence as shown in Fig.3, however, according to the present embodiment as explained above, since the nuclear spin is repeatedly excited in a short time, the Steady State Free Precession (SSFP) is maintained and

S/N of the obtained signals is improved, as a result, the compensation is correctly performed.

In the present invention, which is based on a pulse sequence according to short TR gradient echo method, a group of pulse sequence in which a test gradient magnetic field is applied and another group of pulse sequence in which no test gradient magnetic field is applied are provided and by making use of the echo signals collected from at least one of the groups eddy currents having a long time constant can be measured in a comparatively short measurement time, moreover not only the eddy current induced at the time when the gradient magnetic field falls down but also the eddy current induced at the time when the gradient magnetic field rises up can be likely measured.